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Prediction of Launch Vehicle Noise during Lift-off using a Modified Eldred's Method

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Abstract The jet noise is the main cause of the vibro-acoustic loading and internal noise (noise felt by the payload and critical launch vehicle systems) experienced by the launch vehicle during lift-off phase. Techniques such as water injection are being attempted to reduce the launch vehicle noise during lift-off and its impact on the sensitive payload and sub-systems of the launch vehicle are yet to be studied. The current work deals with estimation of noise levels on the entire launch vehicle using a modified version of Eldred's method. The prediction algorithm takes into account the three dimensional nature of jet deflector and consequent distribution of noise sources. Effect of water injection on the noise levels is also attempted. Results show that due to the three dimensional nature of the sources, the noise levels on the front side are higher than on the umbilical tower side. Employment of water injection is found to decrease the noise levels upto 1.5dB at high frequencies.

Key Words: Launch Vehicle Noise, Water Injection, Noise suppression

1. Introduction

The acoustic loading due to the powerful boosters used in modern day launch vehicles has significant effect on the payload. Several studies have been devoted to prediction and mitigation of the noise generated during launch. This noise is generated by the mixing of highly turbulent jet exhaust from the propulsion system with the ambient air and its reflection from the supporting structures. While sub-scale model studies provide an estimate of noise levels at a few discrete (measured) locations on the scale model, they are quite expensive and time consuming. Using empirical relations, a prediction model can be developed to predict noise levels on the entire vehicle. Eldred(1971) showed that it is possible to predict noise field in the free field region surrounding the launch vehicle with good accuracy. Such an approach is not only inexpensive but also provides good estimates of noise levels encountered by the launch vehicle during launch. In this work a modified version of Eldred is implemented following the work done by others [Varnier (1998), Varnier(2001), Koudriavstev et al(2004), Hayes and Kenny (2009) and Plotkin(2009)] expanding on Eldred's method.

Currently, techniques like water injection are in use to reduce the effect of noise generated during lift-off. Kandula(2008) developed a formulation to predict the reduction in noise levels due to water injection. Tests on static scaled down model of a solid rocket motor employing water injection techniques was carried out by Sankaran(2009). However the consequent impact on the sensitive payload and sub-systems of the launch vehicle are yet to be studied.

In this study, a modified prediction algorithm, based on the earlier version of Eldred's 'Discrete source allocation method II', Eldred(1971) is presented. In addition, the effect of actual three-dimensional nature of jet deflector and consequent distribution of noise sources is also incorporated. A prediction code based on the modified algorithm was developed and applied to a generic launch vehicle scaled down model. Attempts have been made to study the effect of water injection in reduction of acoustic loads on the launch vehicle during launch.

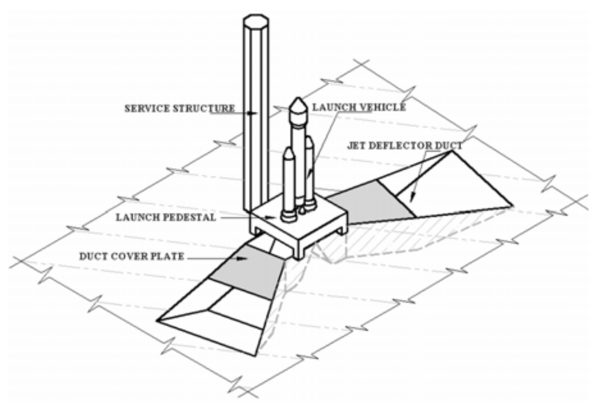


Figure 1 Typical Launch Vehicle environment

2. General Methodology

The prediction is based on the discrete source allocation method II as mentioned in Eldred's work. Here the sources are assumed to be distributed along the centerline of the deflected exhaust stream. The exhaust stream is considered to be divided into a number of slices each acting as a source to noise levels of different frequencies in the 1/3rd octave band. In this work actual three-dimensional nature of jet deflector is included for locating of the sources are calculated to improve the prediction accuracy. The procedure for obtaining the acoustic levels is described in Eldred(1971).

The overall sound power is then found using,

$$W_{OA} = \eta n F U_e \qquad (1)$$

Where, W_{OA} is the overall acoustic power, F is thrust of each engine, n the number of nozzles, Ue fully expanded exit velocity and η is the efficiency factor (0.005)

The length of the supersonic core can be derived from the work by Varnier(2009) which a modification to the expression given by Eldred(1971);

$$\frac{x_t}{D_e} = 1.75\left(1 + 0.38 M_e\right)^2 \qquad (2)$$

The sound power level (SPL) is obtained from the normalized relative power spectrum level by the following relations

$$\mathrm{SPL}_{s,b,p} = L_{w,s,b} - 11 + DI(b,\Theta) \qquad (3)$$

Where, the directivity DI(b,Θ) is obtained using the angle β which is the relative angle between given slice and its position to the point of consideration as shown in Figure 2.

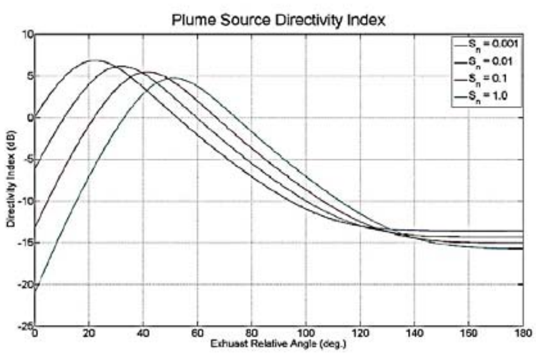


Figure 2 Plot of Directivity index variation with Relative angle from the exhaust at different Strouhal numbers, Plotkin(2009)

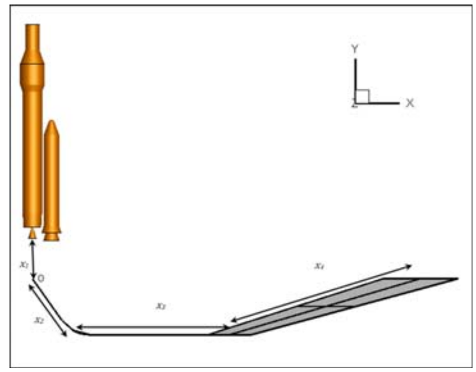
The sound pressure level for any given point (SPL) of the particular frequency (source) is added up logarithmically to account for all the slices and the frequencies,

$$\mathrm{SPL}_{b,p} = 10\log\sum_{s}\mathrm{antilog}\left(\frac{\mathrm{SPL}_{s,b,p}}{10}\right) \qquad (4)$$

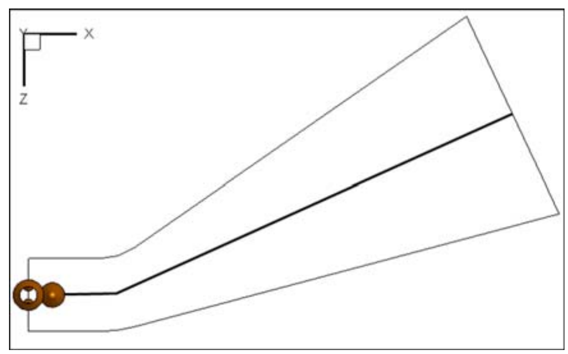
Finally the Overall Sound Pressure Level (OASPL) at given point is calculated by summing up the SPL.

3. Modifications to general methodology

The sources are distributed along the centerline of the jet deflector. The centerline from the nozzle exit and extending along the center of the jet deflector has been divided in 4 regions, X_1, X_2, X_3 and X_4 as shown in Figure 3. X_1 is the distance between the nozzle exit plane and the jet deflector origin mentioned as O which is also origin of the co-ordinate system. Such a configuration allows us to minimize the changes required in the code to calculate the noise levels during different lift-off distances (L/De).



(a)



(b)

Figure 3 A Sketch of axial distances considered for distribution of noise sources for a generic launch vehicle lift-off configuration, (a) Front View (b) Top View

There are certain factors which are to be further considered before applying this method to the actual liftoff flight noise level evaluation. The directivity factor plot may vary for different launch vehicles and its launch environment (Figure 3). The plot has to be replaced by conducting experiments with microphone mounted in the far-field at different relative angles and with different Strouhal numbers. This will lead to more accurate prediction. While obtaining noise levels on the vehicle surface, the diffraction effects should be considered. The effect of reflection from the solid wall should also be taken into account. Further with the presence of boosters, strap-ons etc, a part of the core vehicle is shielded from the noise sources. The noise level at these locations may be smaller than the predicted values as such conditions are not addressed in the prediction. Scattering of sound due to the surface curvature is neglected and must be included to yield a more accurate prediction

4. Effect of Water Injection

The formulation by Kandula(2008) for determination of jet mixing noise reduction due to water injection is incorporated in the algorithm. A control volume as shown in Figure 4 is considered.

Solving equations the governing equations for the given control volume we get the following relation for the effective jet velocity,

$$\frac{u_{j2}}{u_{j1}} = \frac{1}{1+\eta\left(\dot{m}_w/\dot{m}_{j1}\right)}\left[1-\frac{F_d}{\rho_{j1}u^2{}_{j1}A_{j1}}+\frac{\eta\dot{m}_w u_p}{\rho_{j1}u_{j1}{}^2 A_{j1}}\right] \quad (5)$$

Where $\dot{m}_j, A_j, u_j, \rho_j$ are jet parameters that are evaluated at sections 1 and 2. $\dot{m}_w$ the mass flow rate of water in the jet axial direction, η is the fraction of the injected water flow rate that is evaporated, *Fd* is the droplet drag force and u_p is the droplet velocity. c_p is the specific heat capacity at constant pressure

The results obtained are incorporated into the modified Eldred's algorithm as discussed in Section 2.

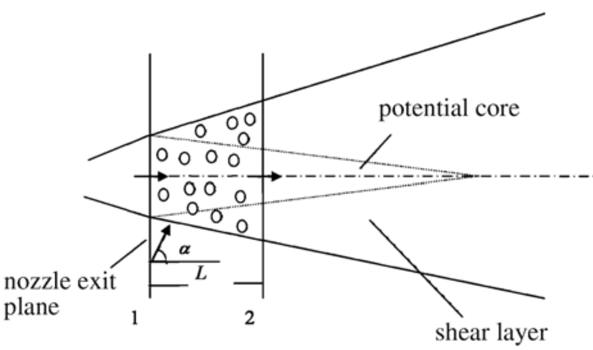


Figure 4 Schematic of the jet configuration with water injection, Kandula(2008)

5. Results and discussions

5.1. Predicted noise levels using the modified Eldred's method

The algorithm based on Eldred's method is used to predict the noise levels of the generic launch vehicle configuration with the incorporation of the 3-D noise source distribution as shown in Figure 3. Figure 5 shows the plot showing the Overall sound pressure level contours both forward side and the leeward side. Though both the strap-ons were considered for the study, only one is shown for clarity.

The noise contours on the entire surface of the launch vehicle could be estimated using the prediction algorithm. It can be seen from the contours that the noise levels on the forward side on the nozzle region is slightly higher than those in the lee-ward side. This is due to the fact that the jet deflector is curved towards the forward direction directing the jet plume away from the launch vehicle and the umbilical tower.

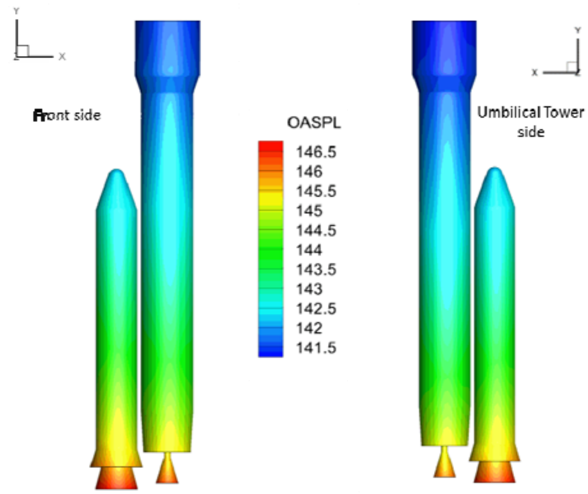


Figure 5 Acoustic Levels(OASPL) obtained from Modified Eldred's method for 3-D source distribution

The 1/3rd Octave spectrum at two locations on the launch vehicle is shown in Figure 6. The solid line denotes noise levels without application of water injection while the dashed line denotes the noise levels when the water injection is employed with WFR=10. Two points were chosen, one at the top of the launch vehicle and the other one close to the nozzle. As expected the noise levels at top being farther away from the jet exhibited lower values than that observed at the location close to the nozzle. The increase in the noise levels at the nozzle end was found higher for higher frequencies. The peak noise level was observed to be at the same frequency irrespective of the location of the point.

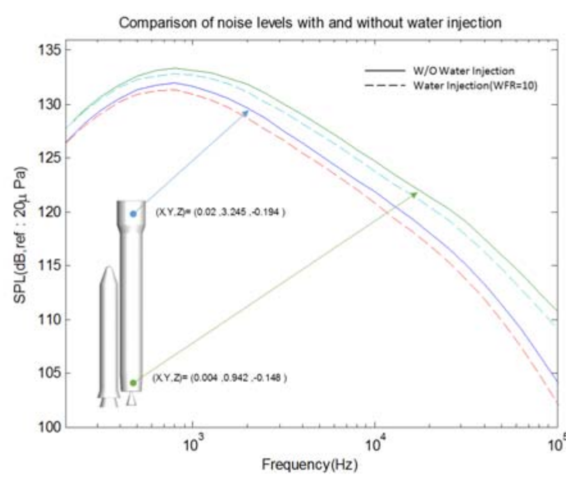


Figure 6 Comparison of 1/3rd Octave band spectrum of noise at two locations with and without use of water injection

5.2. Effect of water injection

Figure 7 shows the effect of water injection (WFR=10) during launch on the acoustic levels for L/De = 0. WFR stands for water flow ratio i.e. mass flow ratio of water injected to the mass flow ratio of the jet. The contours show that the reduction in the noise levels due to water injection is maximum (1.5dB) at the top of the launch vehicle, farthest from the exhaust jet. Towards the nozzle the noise level reduction decreases to a mimimum at the nozzle (0.6dB).

The effect of water injection on the spectrum is seen in Figure 6. The decrease in the noise levels at frequencies lower than the peak frequency is marginal whereas at higher frequencies is much higher. Decrease in noise levels upto 1.5dB is observed for both locations at higher frequencies in the spectra.

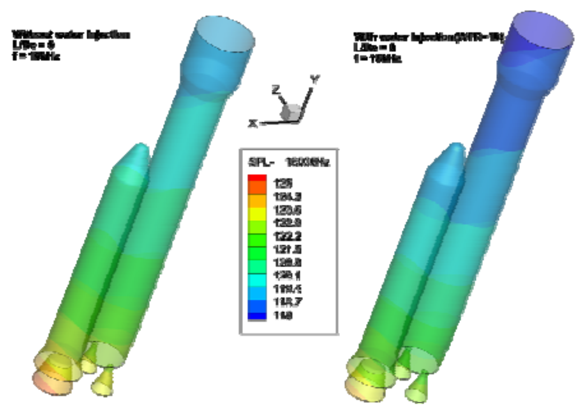


Figure 7 Effect of water injection (WFR=10) on the acoustic levels during launch for (L/De=0) configuration

Conclusion

Noise levels on the surface of the launch vehicles was predicted by modifying Eldred’s method to incorporate three-dimensional source distribution to represent a typical launch environment. The noise contours on the surface of the launch vehicles was computed with and without employment of water injection. It was found that the noise contours on the front side of the launch vehicle was different from that on the rear side (i.e. side facing the umbilical tower) owing to the jet deflector being curved towards the forward direction directing the jet plume away from the launch vehicle and the umbilical tower. The noise spectrum at two different locations indicate that the noise levels are lower at the top and increases towards the nozzle and the magnitude of increase is higher at higher frequencies. The injection of water is found to decrease noise levels upto 1.5dB for higher frequencies. Although the predictions have been made they are subject to a number of factors discussed under section 3 (Modifications to general methodology). Currently work is underway to incorporate these factors in the prediction tool.

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